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Heat stress is a major problem associated with use of encapsulating chemical protective garments. Metabolic and externally imposed heat loads can be degrade cognitive and physical performance and prove life-threating if not adequately extracted from within protective clothing ensembles. Two approaches have historically been used to actively remove heat from encapsulating clothing ensembles: (1) vapor phase cooling, where the heat transfer medium is a vapor such as air; and (2) liquid phase cooling, with water or freon acting as the heat transfer medium. Personal aircrew cooling systems tend to be vapor-based because of weight considerations and the risk of leaking coolant into the aircraft. In addition, air-cooled systems employing evaporative cooling can theoretically remove greater quantities of heat while using less external energy the liquid-based systems dependent on conductive or convective heat exchange. Wearing a helmet, however, compresses the protective hood worn with encapsulating protective garments and produces available airflow to the head and neck. This reduced airflow may limit heat loss from the head and neck and potentially eliminate a major route of body heat loss. The purpose of this study was to examine whether using a chemical protective hood contributes significantly to heat stress in a hot/humid environment.

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IMPACT OF A VENTILATED HOOD ON HEAT STRESS AT HIGH RELATIVE HUMIDITY

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INTRODUCTION

Heat stress is a major problem associated with use of encapsulating chemical protective garments. Metabolic and externally imposed heat loads can degrade cognitive and physical performance and prove life-threating if not adequately extracted from within protective clothing ensembles. Two approaches have historically been used to actively remove heat from encapsulating clothing ensembles: (1) vapor phase cooling, where the heat transfer medium is a vapor such as air; and (2) liquid phase cooling, with water or freon acting as the heat transfer medium. Personal aircrew cooling systems tend to be vapor-based because of weight considerations and the risk of leaking coolant into the aircraft. In addition, air-cooled systems employing evaporative cooling can theoretically remove greater quantities of heat while using less external energy than liquid-based systems dependent on conductive or convective heat exchange. Wearing a helmet, however, compresses the protective hood worn with encapsulating protective garments and reduces available airflow to the head and neck. This reduced airflow may limit heat loss from the head and neck and potentially eliminate a major route of body heat loss. The purpose of this study was to examine whether using a chemical protective hood contributes significantly to heat stress in a hot/humid environment.

MATERIALS AND METHODS

Seven subjects (1 female, 6 males, 23-48 years old) were exposed twice to 35°C ambient temperatures at 75% relative humidity (RH) while performing up to 12 repeated 30 minute rest/work cycles (20 minute rest/10 minute physical work). Subjects wore a ventilated chemical protective ensemble (HAILSS) and helmet with (HER) or without (nHER) isolated head/eye/respiratory protection. The HAILSS below-the-neck ensemble consisted of a nomex/butyl coverall with an internal air distribution system to circulate air (110 l/min) over most of the below neck skin surface. This design closely resembled the previously tested "Dornier" suit (1). When HER was used, the USN AR-5 chemical protective hood and respirator provided above-the-neck coverage with an independent blower system providing head ventilation. Physical work loads consisted of pedaling a bicycle ergometer at 40% VO_{2max}. Subjects also performed a series of cognitive tasks lasting roughly 15 minutes during each rest period. Exposure duration, t, differences between final and initial rectal (ΔT_{re}), forehead (ΔT_{fore}), and neck temperatures (ΔT_{neck}), the rate of rectal temperature change, $\Delta T_{re}/t$, suit cooling air inlet and outlet dry bulb temperatures, T_{db}, suit cooling air outlet wet bulb temperature, T_{wb}, and airflow rate, V_{suit}, were determined for each run.

Evaporative heat, Q_E, extracted by the HAILSS ventilation system was calculated from the difference between outlet and inlet airstream enthalpy, h, given by $\Delta h = h_{out} - h_{in}$. Moist air enthalpy can be calculated from the humidity ratio of moist air, W, and dry bulb temperature, T_{db}, by

[1] $$h = 1.006T_{db} + W(2501 + 1.805T_{db}) \quad \text{(kJ/kg)}$$

where W, a function of relative humidity, ϕ, and the humidity ratio of saturated air, W_s, at a given temperature and pressure is

[2] $$W = \phi W_s/[1+(1-\phi)W_s/0.62198]$$

and $\phi = f(T_{db}, T_{wb})$ (2). Given the ventilation mass flow rate, M_{air}, Q_E can be determined after calculating h_{out} and h_{in}, from

[3] $$Q_E = M_{air}\,\Delta h$$

Convective heat losses were quantified by measuring body surface heat flux with heat flux transducers at four locations (upper arm, chest, thigh, shin). Total body convective heat loss, Q_C, was estimated by calculating the weighted sum of regional heat fluxes

[4] $$Q_C = .2\,(HF_{arm} + HF_{shin}) + .3(HF_{chest} + HF_{thigh})$$

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and from this an estimate of total body heat loss, Q_T, can be obtained from

[5] $Q_T = Q_E + Q_C$

Experimental results were also compared to predicted exposure durations which defined the time required for ventilation to remove sufficient metabolically generated heat for a user to sustain $\Delta t_{re} < 2°C$. This metabolic heat burden can be divided into a resting component and excess heat from mechanical work. An imposed physical workload can be divided into the energy required to perform mechanical work and energy providing addition heat to the body. The average maximum oxygen consumption (a measure of fitness) for a 25 year old 70 kg male is approximately 3.5 liters/min (3). Pedaling a bicycle ergometer at 45% VO_{2max} means that this average 25 year old male experiences an approximate workload of 1.58 l min-1 or 101W (6.1 kJ/min) based on the relationship

[6] $VO_2 = 5.8w_b + 151 + 10.1\, l_w$ (ml/min)

where w_b = body weight (kg) and l_w = workload (4). Since the mechanical efficiency of bicycle pedaling is roughly 30% (4), then this work contributes an additional 4.9 kJ/min of heat to a basal metabolic rate of 84 W (5.0 kJ/min) so that thermal homeostasis requires total removal of 9.9 kJ/min. If a ventilation system cannot totally remove 9.9 kJ/min, excess metabolic heat will increase body heat storage and cause ΔT_{re} to rise.

Statistical Analysis: The Wilcoxin matched pairs test was used to determine whether using HER produced significant differences in Q_E, Q_T, t, ΔT_{re}, ΔT_{fore}, ΔT_{neck}, and $\Delta T_{re}/t$. Correlation between t and Q_E, ΔT_{re}, ΔT_{fore}, and ΔT_{neck} was also assessed. Values are reported as mean ± SEM with differences considered significant at the $\alpha < 0.05$ level.

RESULTS

Table 1 shows that use of an encapsulating hood had no significant impact on mean exposure duration, Q_E, Q_T, ΔT_{re}, ΔT_{neck} or $\Delta T_{re}/t$. Figure 1 shows the significant correlation observed between t and ΔT_{fore} ($r = 0.843$, $p < 0.01$) though hood use did not significantly effect ΔT_{fore}. No other significant correlations between t and other variables were observed. Figure 2 shows that using a hood had no significant effect on total body heat loss.

Table 1. Mean human exposures results (mean ±S.E.M.

Variable	hood	no hood
t	104.6 ± 9.5	105.7 ± 7.4
ΔT_{re}	1.2 ± 0.2	1.1 ± 0.1
ΔT_{fore}	4.4 ± 0.7	4.1 ± 0.4
ΔT_{neck}	3.9 ± 0.3	4.1 ± 0.3
$\Delta T_{re}/t$	0.7 ± 0.1	0.7 ± 0.1
Q_E	4.7 ± 1.8	4.8 ± 1.8

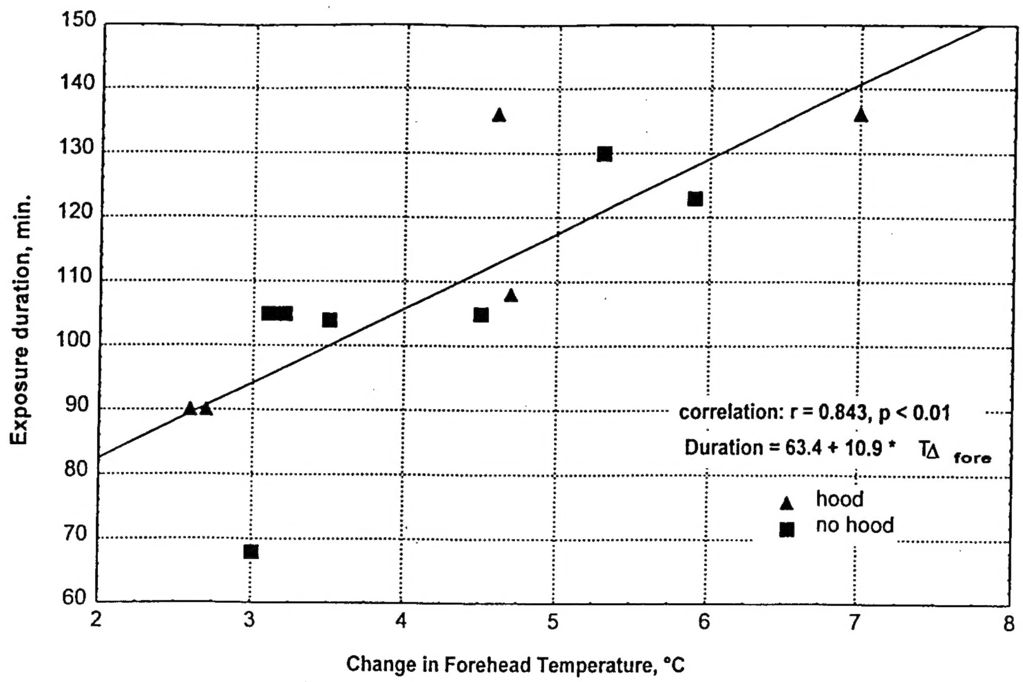

Figure 1 Correlation between change in forehead temperature and exposure duration. r = 0.843, p < 0.01

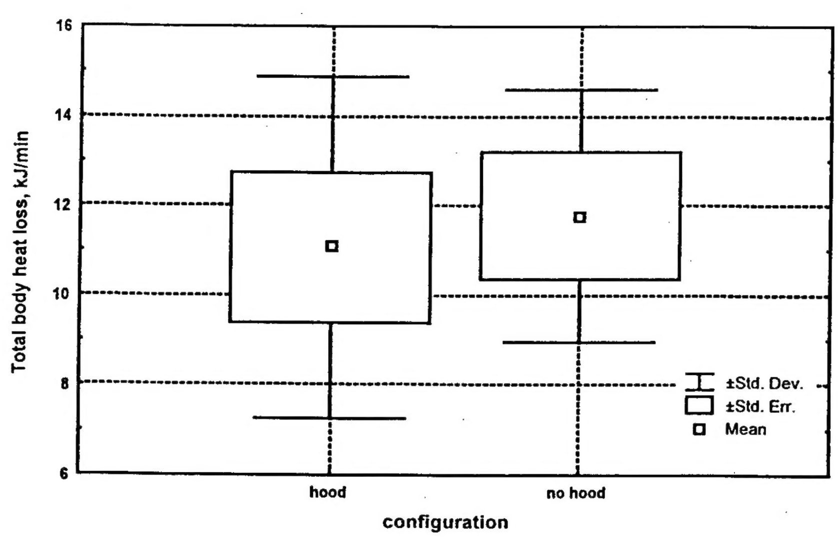

Figure 2. The effect of using a ventilated encapsulating hood on total body heat loss.

DISCUSSION

The ultimate goal of this work is to maximize cooling system efficiency. Done efficiently, head cooling diminishes sweating, lowers rectal and mean skin temperatures, and extends exposure times in the heat despite the head and neck accounting for only 7-10% of body surface area. Thermoregulation is particularly sensitive to extracting heat from the head because selectively cooling the brain reduces hypothalamic temperature that diminishes autonomic responses to heat stress. Facial cooling produces some of the same responses as head cooling though to a lesser extent.

The results from this study suggest that thermoregulation is unaffected by use of a cooling hood under these experimental conditions. Two factors may explain the lack of significant differences in heat losses or rectal temperatures. First, HER cooling depends on evaporating sweat from the head with unconditioned ventilation air drawn from the surrounding environment. If ambient air is sufficiently humid, the water vapor concentration gradient between ventilation air and the head/neck skin surface will be small. Consequently, evaporation will be greatly diminished and cooling reduced to perhaps insignificant levels. In this case, ventilation will be worthless and head temperatures in both HER and nHER would rise uncontrolably. It seems reasonable to conclude that this did not occur because ΔT_{fore} rose linearly not exponentially.

An alternative explanation is that the HER fits fairly tight about the head, particularly with a helmet in place, which may restrict the volume of air flowing over the top of the head. Insufficient ventilation may reduce head cooling efficiency and reduce thermoregulatory effectiveness to approximately that of facial cooling. Given that study results are consistant with this explanation, this explanation seems more plausible.

Considerable increases in ΔT_{re} indicate that homeostasis was not achieved despite whole body heat losses exceeding 9.9 kJ/min. This can probably be best explained by considering the assumptions made in the model. First, the heat loss model employed assumed a 25 year old male and study subjects were generally older. This implies less efficient use of metabolic energy and as a corralary less efficient conversion to mechanical energy on the ergometer. While these results do not directly impact on the current investigation, the disparity between predicted and actual T_{re} suggest further study would be warrented.

CONCLUSIONS

Performance of the proposed cooling system is degraded when operated in a high humidity environment system. This suggests that ancillary inlet air cooling is necessary when used in high temperature/humidity conditions common during temperate or tropical summers.

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